

# Right-handed neutrino dark matter in the classically conformal $U(1)'$ extended Standard Model

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## Abstract

We consider the dark matter (DM) scenario in the context of the classically conformal  $U(1)'$  extended standard model (SM), with three right-handed neutrinos (RHNs) and the  $U(1)'$  Higgs field. The model is free from all the  $U(1)'$  gauge and gravitational anomalies in the presence of the three RHNs. We introduce a  $Z_2$ -parity in the model, under which an odd-parity is assigned to one RHN, while all the other particles is assigned to be  $Z_2$ -even, and hence the  $Z_2$ -odd RHN serves as a DM candidate. In this model, the  $U(1)'$  gauge symmetry is radiatively broken through the Coleman-Weinberg mechanism, by which the electroweak symmetry breaking is triggered. There are three free parameters in our model, the  $U(1)'$  charge of the SM Higgs doublet ( $x_H$ ), the new  $U(1)'$  gauge coupling ( $g_X$ ), and the  $U(1)'$  gauge boson ( $Z'$ ) mass ( $m_{Z'}$ ), which are severely constrained in order to solve the electroweak vacuum instability problem, and satisfy the LHC Run-2 bounds from the search for  $Z'$  boson resonance. In addition to these constraints, we investigate the RHN DM physics. Because of the nature of classical conformality, we find that a RHN DM pair mainly annihilates into the SM particles through the  $Z'$  boson exchange. This is the so-called  $Z'$ -portal DM scenario. Combining the electroweak vacuum stability condition, the LHC Run-2 bounds, and the cosmological constraint from the observed DM relic density, we find that all constrains complementarily work to narrow down the allowed parameter regions, and, especially, exclude  $m_{Z'} \lesssim 3.5$  TeV.

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# 1 Introduction

There are important missing pieces in the Standard Model (SM), for example, a candidate for the dark matter (DM), and tiny neutrino masses and their flavor mixings. The SM should be extended so as to supplement these missing pieces. The so-called seesaw mechanism is a natural way to reproduce the tiny neutrino masses [1–5], where heavy Majorana right-handed neutrinos (RHNs) are introduced. The minimal gauged  $B-L$  model [6–11] is one of the simplest extensions of the SM with an extra gauge symmetry, in which the accidentally anomaly-free global  $B-L$  (baryon number minus lepton number) in the SM is gauged. Three RHNs play an essential roll to cancel the gauge and gravitational anomalies of the model. Associated with the  $B-L$  symmetry breaking, the RHNs acquire their Majorana masses, and hence the seesaw mechanism is automatically implemented. The minimal  $B-L$  model can be generalized to the so-called minimal  $U(1)'$  model [12]. Here, the  $U(1)'$  gauge group is defined as a linear combination of the  $U(1)_{B-L}$  and the SM  $U(1)_Y$  gauge groups, so that the  $U(1)'$  model is anomaly-free.

In our previous work [13, 14], we have investigated the minimal  $U(1)'$  model with classically conformal invariance.<sup>4</sup> In this model, the  $U(1)'$  gauge symmetry is radiatively broken though the Coleman-Weinberg (CW) mechanism [51]. Given a negative mixing quartic coupling between the SM Higgs and the  $U(1)'$  Higgs fields, once the  $U(1)'$  Higgs field develops a vacuum expectation value (VEV), a negative mass squared of the SM Higgs doublet is generated, and thus the electroweak symmetry breaking is naturally triggered. In this model context, we have investigated the electroweak vacuum instability problem in the SM. Employing the renormalization group (RG) equations at the two-loop level and the central values for the world average masses of the top quark ( $m_t = 173.34$  GeV [52]) and the Higgs boson ( $m_h = 125.09$  GeV [53]), we have performed parameter scans to identify the parameter region for resolving the electroweak vacuum instability problem. We have also investigated the ATLAS and CMS search limits at the LHC Run-2 (2015) for the  $U(1)'$  gauge boson ( $Z'$ ) [54, 55], and identified the allowed parameter regions in our model. Combining the constraints from the electroweak vacuum stability and the LHC Run-2 results, we have found a lower bound on the  $Z'$  boson mass. We also have calculated self-energy corrections to the SM Higgs doublet field through the heavy states, the right-handed neutrinos and the  $Z'$  boson, and have found the naturalness bound as  $m_{Z'} \lesssim 6$  TeV, in order to reproduce the right electroweak scale for the fine-tuning level better than 10%.

The so-called weakly interacting massive particle (WIMP) is one of the most promising candidates of the DM in our Universe, which is in thermal equilibrium in the early Universe. Among many possibilities, a simple way to introduce a WIMP DM in the minimal  $U(1)'$  model has been proposed in [56] (see also [57]), where  $Z_2$ -parity is introduced and an odd-parity is assigned to one RHN, while all the other particles is assigned to be  $Z_2$ -even. We adapt this scheme in our minimal  $U(1)'$  model with the classically conformal invariance, and the  $Z_2$ -odd RHN is a DM candidate, while the other two RHNs are utilized for the seesaw mechanism. Note that only two RHNs are sufficient to reproduce the neutrino oscillation data, and the observed baryon asymmetry in the Universe through leptogenesis [58]. This system is called the minimal seesaw [59, 60]. In our model, there are two ways for the RHN DM to interact with the SM

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<sup>4</sup> See Refs. [15–50] for recent work on new physics models with classically conformal invariance.

particles. One is mediated by the  $Z'$  boson ( $Z'$ -portal) and the other is by the two Higgs bosons (Higgs portal) which are two mass eigenstates consisting of the SM Higgs and the  $U(1)'$  Higgs bosons. Recently, the  $Z'$ -portal DM scenarios [61–89] have been intensively investigated, while the Higgs portal RHN DM scenarios [56, 90, 91] have been analyzed in detail.

In this paper, we consider the classically conformal  $U(1)'$  extended SM with the RHN DM. As we mentioned above, the allowed parameter regions in the classically conformal model are severely constrained in order to solve the electroweak vacuum instability problem, and to satisfy the LHC limits from the search for  $Z'$  boson resonance. In addition to these constraints, we will investigate the RHN DM physics. Because of the nature of classical conformality, we find the mass mixing between the SM Higgs and the  $U(1)'$  Higgs bosons is very small, so that the RHN DM pair annihilation process mediated by the Higgs bosons is highly suppressed. Therefore, we focus on the study of the  $Z'$ -portal RHN DM [78, 87], and identify allowed parameter regions to reproduce the observed DM relic density from the Planck 2015 result [92]. We will show that the DM physics, LHC phenomenology, and the electroweak vacuum stability condition complementarily work to narrow down the allowed parameter regions.

This paper is organized as follows: In the next section, we introduce the classically conformal  $U(1)'$  extended SM with  $Z'$ -portal RHN DM. We briefly review our previous work on the classically conformal  $U(1)'$  model [13, 14]. In Sec. 3, we calculate the relic density of the  $Z'$ -portal RHN DM. In Sec. 4, we study the  $Z'$  boson production at the LHC Run-2 (2016) [93, 94], and obtained the constraints on the model parameter space from the search results of the  $Z'$  boson resonance by the ATLAS and the CMS Collaborations. In Sec. 5, we combine all the results in the previous sections and narrow allowed regions. The last section is devoted to conclusions.

## 2 The classically conformal $U(1)'$ extended SM with RHN DM

In this section, we will briefly review the results in Ref. [14]. Although the model is extended to incorporate the RHN DM, the results presented here are essentially the same as those in Ref. [14].

### 2.1 The model

The model we will investigate is the anomaly-free  $U(1)'$  extension of the SM with the classically conformal invariance, which is based on the gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$ . The particle contents of the model are listed in Table 1. In addition to the SM particle content, three generations of RHNs  $\nu_R^i$  and a  $U(1)'$  Higgs field  $\Phi$  are introduced. We also introduce the  $Z_2$  parity [56], and assign an odd parity to one RHN  $\nu_R^3$ , while the other particles, including  $\nu_R^1$  and  $\nu_R^2$ , have even parity. The conservation of  $Z_2$  parity ensures the stability of  $\nu_R^3$ , which is a unique candidate of the DM in our model.

The covariant derivative, which is relevant to  $U(1)_Y \times U(1)'$ , is defined as

$$D_\mu \equiv \partial_\mu - i \begin{pmatrix} Y_1 & Y_X \end{pmatrix} \begin{pmatrix} g_1 & g_{1X} \\ g_{X1} & g_X \end{pmatrix} \begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}, \quad (2.1)$$

	SU(3) <sub>c</sub>	SU(2) <sub>L</sub>	U(1) <sub>Y</sub>	U(1)'	Z <sub>2</sub>
$q_L^i$	<b>3</b>	<b>2</b>	+1/6	$x_q = \frac{1}{3}x_H + \frac{1}{6}x_\Phi$	+
$u_R^i$	<b>3</b>	<b>1</b>	+2/3	$x_u = \frac{4}{3}x_H + \frac{1}{6}x_\Phi$	+
$d_R^i$	<b>3</b>	<b>1</b>	-1/3	$x_d = -\frac{2}{3}x_H + \frac{1}{6}x_\Phi$	+
$\ell_L^i$	<b>1</b>	<b>2</b>	-1/2	$x_\ell = -x_H - \frac{1}{2}x_\Phi$	+
$\nu_R^{1,2}$	<b>1</b>	<b>1</b>	0	$x_\nu = -\frac{1}{2}x_\Phi$	+
$\nu_R^3$	<b>1</b>	<b>1</b>	0	$x_\nu = -\frac{1}{2}x_\Phi$	-
$e_R^i$	<b>1</b>	<b>1</b>	-1	$x_e = -2x_H - \frac{1}{2}x_\Phi$	+
$H$	<b>1</b>	<b>2</b>	+1/2	$x_H = x_H$	+
$\Phi$	<b>1</b>	<b>1</b>	0	$x_\Phi = x_\Phi$	+

Table 1: Particle contents of the U(1)' extended SM with Z<sub>2</sub> parity. In addition to the SM particle contents, three generations of RHNs  $\nu_R^i$  ( $i = 1, 2, 3$  denotes the generation index) and U(1)' Higgs field  $\Phi$  are introduced. Under Z<sub>2</sub> parity, the only one RHN  $\nu_R^3$  is odd, while the other particles, including  $\nu_R^1$  and  $\nu_R^2$ , are even.

where  $Y_1$  ( $Y_X$ ) is U(1)<sub>Y</sub> (U(1)') charge of a particle, and the gauge coupling  $g_{X1}$  and  $g_{1X}$  are introduced associated with a kinetic mixing between the two U(1) gauge bosons. In order to reproduce observed fermion masses and flavor mixings, we introduce the following Yukawa interactions:

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} = & - \sum_{i=1}^3 \sum_{j=1}^3 Y_u^{ij} \bar{q}_L^i \tilde{H} u_R^j - \sum_{i=1}^3 \sum_{j=1}^3 Y_d^{ij} \bar{q}_L^i H d_R^j - \sum_{i=1}^3 \sum_{j=1}^3 Y_e^{ij} \bar{\ell}_L^i H e_R^j \\
& - \sum_{i=1}^3 \sum_{j=1}^2 Y_\nu^{ij} \bar{\ell}_L^i \tilde{H} \nu_R^j - \sum_{i=1}^3 Y_M^i \Phi \bar{\nu}_R^{ic} \nu_R^i + \text{h.c.},
\end{aligned} \tag{2.2}$$

where  $\tilde{H} \equiv i\tau^2 H^*$ , and the fourth and fifth terms in the right-handed side are for the seesaw mechanism to generate neutrino masses. Without loss of generality, the Majorana Yukawa couplings in the fifth term are already diagonalized in our basis. Because of the Z<sub>2</sub> parity, only two generation RHNs are involved in the neutrino Dirac Yukawa couplings and hence the neutrino Dirac mass matrix is 2 by 3. Once the U(1)' Higgs field  $\Phi$  develops a VEV, the U(1)' symmetry is broken and the Majorana mass terms for the RHNs are generated. After the electroweak symmetry breaking, the seesaw mechanism [1–5] is automatically implemented, except that only two generation RHNs are relevant. This system is the minimal seesaw [59, 60], which possesses a number of free parameters  $Y_\nu^{ij}$  and  $Y_M^j$  ( $i = 1, 2, 3$ ,  $j = 1, 2$ ) enough to reproduce the neutrino oscillation data with a prediction of one massless eigenstate.

In the particle contents, the two parameters ( $x_H$  and  $x_\Phi$ ) reflect the fact that the U(1)' gauge group can be defined as a linear combination of the SM U(1)<sub>Y</sub> and the U(1)<sub>B-L</sub> gauge groups. Since the U(1)' gauge coupling  $g_X$  is a free parameter of the model and it always appears as a product  $x_\Phi g_X$  or  $x_H g_X$ , we fix  $x_\Phi = 2$  without loss of generality throughout this paper. This convention excludes the case that U(1)' gauge group is identical with the SM

$U(1)_Y$ . The choice of  $(x_H, x_\Phi) = (0, 2)$  corresponds to the  $U(1)_{B-L}$  model. Another example is  $(x_H, x_\Phi) = (-1, 2)$ , which corresponds to the SM with the so-called  $U(1)_R$  symmetry. When we choose  $(x_H, x_\Phi) = (-16/41, 2)$ , the beta function of  $g_{X1}$  ( $g_{1X}$ ) at the 1-loop level has only terms proportional to  $g_{X1}$  ( $g_{1X}$ ) [13]. This is the orthogonal condition between the  $U(1)_Y$  and  $U(1)'$  at the 1-loop level, under which  $g_{X1}$  and  $g_{1X}$  do not evolve once we have set  $g_{X1} = g_{1X} = 0$  at an energy scale.

Imposing the classically conformal invariance, the scalar potential is given by

$$V = \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_{\text{mix}} (H^\dagger H) (\Phi^\dagger \Phi), \quad (2.3)$$

where the mass terms are forbidden by the conformal invariance. If  $\lambda_{\text{mix}}$  is negligibly small, we can analyze the Higgs potential separately for  $\Phi$  and  $H$  as a good approximation. This will be justified in the following subsections. When the Majorana Yukawa couplings  $Y_M^i$  are negligible compared to the  $U(1)'$  gauge coupling, the  $\Phi$  sector is identical with the original CW model [51], so that the radiative  $U(1)'$  symmetry breaking will be achieved. Once  $\Phi$  develops a VEV through the CW mechanism, the tree-level mass term for the SM Higgs doublet is effectively generated through  $\lambda_{\text{mix}}$  in Eq. (2.3). Taking  $\lambda_{\text{mix}}$  negative, the induced mass squared for the Higgs doublet is negative and, as a result, the electroweak symmetry breaking is driven in the same way as in the SM.

## 2.2 Radiative $U(1)'$ gauge symmetry breaking

Assuming  $\lambda_{\text{mix}}$  is negligibly small, we first analyze the  $U(1)'$  Higgs sector. Without mass terms, the Coleman-Weinberg potential [51] at the 1-loop level is found to be

$$V(\phi) = \frac{\lambda_\Phi}{4} \phi^4 + \frac{\beta_\Phi}{8} \phi^4 \left( \ln \left[ \frac{\phi^2}{v_\phi^2} \right] - \frac{25}{6} \right), \quad (2.4)$$

where  $\phi/\sqrt{2} = \Re[\Phi]$ , and we have chosen the renormalization scale to be the VEV of  $\Phi$  ( $\langle \phi \rangle = v_\phi$ ). Here, the coefficient of the 1-loop quantum corrections is given by

$$\begin{aligned} \beta_\Phi &= \frac{1}{16\pi^2} \left[ 20\lambda_\Phi^2 + 6x_\Phi^4 (g_{X1}^2 + g_X^2)^2 - 16 \sum_i (Y_M^i)^4 \right] \\ &\simeq \frac{1}{16\pi^2} \left[ 6(x_\Phi g_X)^4 - 16 \sum_i (Y_M^i)^4 \right], \end{aligned} \quad (2.5)$$

where in the last expression, we have used  $\lambda_\Phi^2 \ll (x_\Phi g_X)^4$  as usual in the CW mechanism and set  $g_{X1} = g_{1X} = 0$  at  $\langle \phi \rangle = v_\phi$ , for simplicity. The stationary condition  $dV/d\phi|_{\phi=v_\phi} = 0$  leads to

$$\lambda_\Phi = \frac{11}{6} \beta_\Phi, \quad (2.6)$$

and this  $\lambda_\Phi$  is nothing but a renormalized self-coupling at  $v_\phi$  defined as

$$\lambda_\Phi = \frac{1}{3!} \left. \frac{d^4 V(\phi)}{d\phi^4} \right|_{\phi=v_\phi}. \quad (2.7)$$

For more detailed discussion, see Ref. [32].

Associated with this radiative  $U(1)'$  symmetry breaking (as well as the electroweak symmetry breaking), the  $U(1)'$  gauge boson ( $Z'$  boson), the Majorana RHNs  $\nu_R^{1,2}$ , and the RHN DM particle  $\nu_R^3$  acquire their masses as

$$m_{Z'} = \sqrt{(x_\Phi g_X v_\phi)^2 + (x_H g_X v_h)^2} \simeq x_\Phi g_X v_\phi, \quad m_{N^{1,2}} = \sqrt{2} Y_M^{1,2} v_\phi, \quad m_{\text{DM}} = \sqrt{2} Y_M^3 v_\phi, \quad (2.8)$$

where  $v_h = 246$  GeV is the SM Higgs VEV, and we have used  $x_\Phi v_\phi \gg x_H v_h$ , which will be verified below. In this paper, we assume degenerate masses for  $\nu_R^{1,2}$ , ( $Y_M^1 = Y_M^2 = y_M$ , equivalently,  $m_{N^{1,2}} = m_N$ ), for simplicity. The  $U(1)'$  Higgs boson mass is given by

$$\begin{aligned} m_\phi^2 &= \left. \frac{d^2 V}{d\phi^2} \right|_{\phi=v_\phi} = \beta_\Phi v_\phi^2 \simeq \frac{1}{8\pi^2} (3(x_\Phi g_X)^4 - 16y_M^4 - 8y_{\text{DM}}^4) v_\phi^2 \\ &\simeq \frac{1}{8\pi^2} \frac{3m_{Z'}^4 - 4m_N^4 - 2m_{\text{DM}}^4}{v_\phi^2}, \end{aligned} \quad (2.9)$$

where  $y_{\text{DM}} = Y_M^3$ . When the Yukawa couplings are negligibly small, this equation reduces to the well-known relation derived in the original paper by Coleman-Weinberg [51]. For a sizable Majorana mass, this formula indicates that the potential minimum disappears, so that there is an upper bound on the RHN mass for the  $U(1)'$  symmetry to be broken radiatively. This is in fact the same reason why the CW mechanism in the SM Higgs sector fails to break the electroweak symmetry when the top Yukawa coupling is large as observed. In order to avoid the destabilization of the  $U(1)'$  Higgs potential, we simply set  $m_{Z'}^4 \gg m_N^4$  in the following analysis, while  $m_{\text{DM}} \simeq m_{Z'}/2$  as we will find in the next section. Note that this condition does not mean that the Majorana RHNs must be very light, even though a factor difference between  $m_{Z'}$  and  $m_N$  is enough to satisfy the condition. For simplicity, we set  $y_M = 0$  at  $v_\phi$  in the following RG analysis as an approximation.

### 2.3 Electroweak symmetry breaking

Let us now consider the SM Higgs sector. In our model, the electroweak symmetry breaking is achieved in a very simple way. Once the  $U(1)'$  symmetry is radiatively broken, the SM Higgs doublet mass is generated through the mixing quartic term between  $H$  and  $\Phi$  in the scalar potential in Eq. (2.3),

$$V(h) = \frac{\lambda_H}{4} h^4 + \frac{\lambda_{\text{mix}}}{4} v_\phi^2 h^2, \quad (2.10)$$

where we have replaced  $H$  by  $H = 1/\sqrt{2}(0, h)$  in the unitary gauge. Choosing  $\lambda_{\text{mix}} < 0$ , the electroweak symmetry is broken in the same way as in the SM [25, 26]. However, we should note that a crucial difference from the SM is that, in our model, the electroweak symmetry breaking originates from the radiative breaking of the  $U(1)'$  gauge symmetry. At the tree level, the stationary condition  $V'|_{h=v_h} = 0$  leads to the relation  $|\lambda_{\text{mix}}| = 2\lambda_H(v_h/v_\phi)^2$ , and the Higgs boson mass  $m_h$  is given by

$$m_h^2 = \left. \frac{d^2 V}{dh^2} \right|_{h=v_h} = |\lambda_{\text{mix}}| v_\phi^2 = 2\lambda_H v_h^2. \quad (2.11)$$



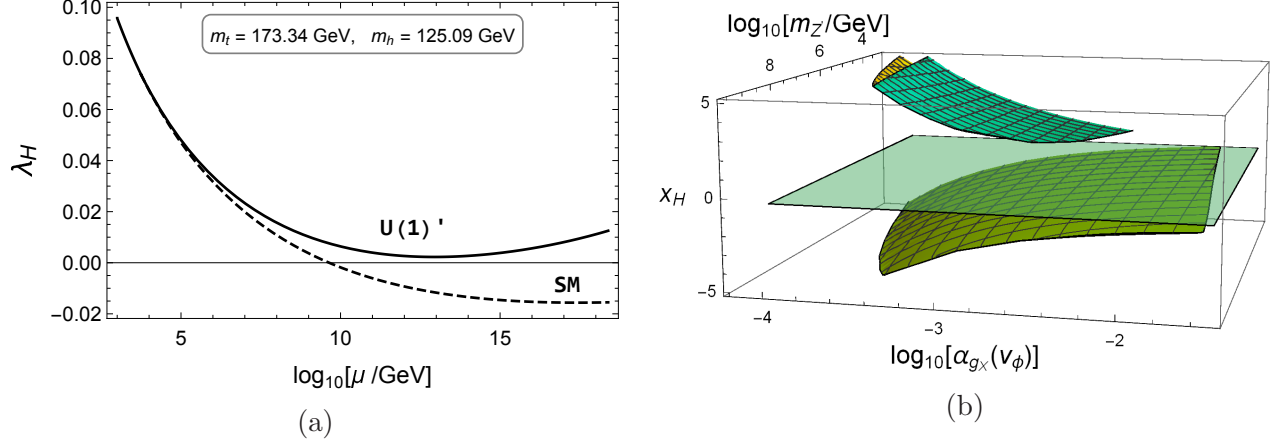


Figure 1: (a) The evolutions of the Higgs quartic coupling  $\lambda_H$  (solid line) for the inputs  $m_t = 173.34$  GeV and  $m_h = 125.09$  GeV, along with the SM case (dashed line). Here, we have taken  $x_H = -0.575$ ,  $m_{Z'} = 4$  TeV and  $\alpha_{g_X} = 0.01$ , which corresponds to  $v_\phi = 5.64$  TeV and  $g_X(v_\phi) = 0.354$ . (b) The result of the three-dimensional parameter scans for  $v_\phi$ ,  $g_X$  and  $x_H$ , shown in  $(m_{Z'}/\text{GeV}, \alpha_{g_X}, x_H)$  parameter space with  $m_{Z'} \simeq x_\Phi g_X v_\phi$ . As a reference, a horizontal plane for  $x_H = -16/41$  is shown, which corresponds to the orthogonal case.

In the following RG analysis, this is used as the boundary condition for  $\lambda_{\text{mix}}$  at the renormalization scale  $\mu = v_\phi$ . Note that since  $\lambda_H \sim 0.1$  and  $v_\phi \gtrsim 10$  TeV by the large electron-positron collider (LEP) constraint [95–97],  $|\lambda_{\text{mix}}| \lesssim 10^{-5}$ , which is very small.

In our discussion about the  $U(1)'$  symmetry breaking, we neglected  $\lambda_{\text{mix}}$  by assuming it to be negligibly small. Here we justify this treatment. In the presence of  $\lambda_{\text{mix}}$  and the Higgs VEV, Eq. (2.6) is modified as

$$\lambda_\Phi = \frac{11}{6}\beta_\Phi + \frac{|\lambda_{\text{mix}}|}{2} \left( \frac{v_h}{v_\phi} \right)^2 \simeq \frac{1}{2v_\phi^4} \left( \frac{11}{8\pi^2} m_{Z'}^4 + m_h^2 v_h^2 \right). \quad (2.12)$$

Considering the current LHC Run-2 bound from search for  $Z'$  boson resonances [93,94],  $m_{Z'} \gtrsim 4$  TeV, we find that the first term in the parenthesis in the last equality is 5 orders of magnitude greater than the second term, and therefore we can analyze the two Higgs sectors separately.

## 2.4 Solving the electroweak vacuum instability

In the SM with the observed Higgs boson mass of  $m_h = 125.09$  GeV [53], the RG evolution of the SM Higgs quartic coupling shows that the running coupling becomes negative at the intermediate scale  $\mu \simeq 10^{10}$  GeV [98] for  $m_t = 173.34$  GeV [52], and hence the electroweak vacuum is unstable. In our  $U(1)'$  extended SM, however, there is a parameter region to solve this electroweak vacuum instability problem [13,14].<sup>5</sup> There are only three free parameters in our model,  $x_H$ ,  $v_\phi$ , and  $g_X$ , which are also interpreted as  $x_H$ ,  $m_{Z'}$ , and  $\alpha_{g_X} = g_X^2/(4\pi)$ . Inputs of the couplings at  $v_\phi$  are determined by these three parameters. In Fig. 1(a), we show the

<sup>5</sup> In the absence of the classical conformal invariance, the electroweak vacuum instability problem has been investigated in Refs. [82,99–101].

RG evolution of the SM Higgs quartic coupling in our model (solid line), along with the SM result (dashed line). Here, we have taken  $x_H = -0.575$ ,  $m_{Z'} = 4$  TeV and  $\alpha_{g_X} = 0.01$ , which corresponds to  $v_\phi = 5.64$  TeV and  $g_X(v_\phi) = 0.354$ , as an example. The Higgs quartic coupling remains positive all the way up to the Planck mass scale, so the electroweak vacuum instability problem is solved.

In order to identify a parameter region to resolve the electroweak vacuum instability, we perform parameter scans for the free parameters  $x_H$ ,  $v_\phi$  and  $g_X$ . In this analysis, we impose several conditions on the running couplings at  $v_\phi \leq \mu \leq M_P$  ( $M_P = 2.44 \times 10^{18}$  GeV is the reduced Planck mass): stability conditions of the Higgs potential ( $\lambda_H, \lambda_\Phi > 0$ ), and the perturbative conditions that all the running couplings remain in the perturbative regime, namely,  $g_i^2$  ( $i = 1, 2, 3$ ),  $g_X^2$ ,  $g_{X1}^2$ ,  $g_{1X}^2 < 4\pi$  and  $\lambda_H, \lambda_\Phi, \lambda_{\text{mix}} < 4\pi$ . For theoretical consistency, we also impose a condition that the 2-loop beta functions are smaller than the 1-loop beta functions (see Ref. [14] for detail). In Fig. 1(b), we show the result of our parameter scans in the three-dimensional parameter space of  $(m_{Z'}, \alpha_{g_X}, x_H)$ . As a reference, we show a horizontal plane corresponding to the orthogonal case  $x_H = -16/41$ . There is no overlapping of the plane with the resultant parameter regions to resolve the electroweak vacuum instability.

## 2.5 Naturalness bounds from SM Higgs mass corrections

Once the classically conformal symmetry is radiatively broken by the CW mechanism, the masses for the  $Z'$  boson and the Majorana RHNs are generated, and they contribute to self-energy corrections of the SM Higgs doublet. If the  $U(1)'$  gauge symmetry breaking scale is very large, the self-energy corrections may exceed the electroweak scale and require us to fine-tune the model parameters in reproducing the correct electroweak scale. See [102] for related discussions. As heavy states, we have the RHNs and  $Z'$  boson, whose masses are generated by the  $U(1)'$  gauge symmetry breaking.

Since the original theory is classically conformal and defined as a massless theory, the self-energy corrections to the SM Higgs doublet originate from corrections to the mixing quartic coupling  $\lambda_{\text{mix}}$ . Thus, what we calculate to derive the naturalness bounds are quantum corrections to the term  $\lambda_{\text{mix}} h^2 \phi^2$  in the effective Higgs potential

$$V_{\text{eff}} \supset \frac{\lambda_{\text{mix}}}{4} h^2 \phi^2 + \frac{\beta_{\lambda_{\text{mix}}}}{8} h^2 \phi^2 (\ln [\phi^2] + C), \quad (2.13)$$

where the logarithmic divergence and the terms independent of  $\phi$  are all encoded in  $C$ . Here, the major contributions to quantum corrections are from the  $Z'$  boson loops:

$$\beta_{\lambda_{\text{mix}}} \supset \frac{12x_H^2 x_\Phi^2 g_X^4}{16\pi^2} - \frac{4(19x_H^2 + 10x_H x_\Phi + x_\Phi^2) x_\Phi^2 y_t^2 g_X^4}{(16\pi^2)^2}, \quad (2.14)$$

where the first term is from the one-loop diagram, and the second one is from the two-loop diagram [25, 26] involving the  $Z'$  boson and the top quark. By adding a counter-term, we renormalize the coupling  $\lambda_{\text{mix}}$  with the renormalization condition,

$$\left. \frac{\partial^4 V_{\text{eff}}}{\partial h^2 \partial \phi^2} \right|_{h=0, \phi=v_\phi} = \lambda_{\text{mix}}, \quad (2.15)$$



where  $\lambda_{\text{mix}}$  is the renormalized coupling. As a result, we obtain

$$V_{\text{eff}} \supset \frac{\lambda_{\text{mix}}}{4} h^2 \phi^2 + \frac{\beta_{\lambda_{\text{mix}}}}{8} h^2 \phi^2 \left( \ln \left[ \frac{\phi^2}{v_\phi} \right] - 3 \right). \quad (2.16)$$

Substituting  $\phi = v_\phi$ , we obtain the SM Higgs self-energy correction as

$$\begin{aligned} \Delta m_h^2 &= -\frac{3}{4} \beta_{\lambda_{\text{mix}}} v_\phi^2 \\ &\sim -\frac{9}{4\pi} x_H^2 \alpha_{g_X} m_{Z'}^2 + \frac{3m_t^2}{32\pi^3 v_h^2} (19x_H^2 + 20x_H + 4) \alpha_{g_X} m_{Z'}^2. \end{aligned} \quad (2.17)$$

For the stability of the electroweak vacuum, we impose  $\Delta m_h^2 \lesssim m_h^2$  as the naturalness. The most important contribution to  $\Delta m_h^2$  is the first term of Eq. (2.17) generated through the one-loop diagram with the  $Z'$  gauge boson, and the second term becomes important in the case of the  $U(1)_{B-L}$  model, where  $x_H = 0$ .

If  $\Delta m_h^2$  is much larger than the electroweak scale, we need a fine-tuning of the tree-level Higgs mass ( $|\lambda_{\text{mix}}| v_\phi^2/2$ ) to reproduce the correct SM Higgs VEV,  $v_h = 246$  GeV. We simply evaluate a fine-tuning level as

$$\delta = \frac{m_h^2}{2|\Delta m_h^2|}. \quad (2.18)$$

Here,  $\delta = 0.1$ , for example, indicates that we need to fine-tune the tree-level Higgs mass squared at the 10% accuracy level.

### 3 Relic density of the RHN DM

In this section, we calculate the thermal relic density of the RHN DM and identify the model parameter region to be consistent with the Planck 2015 measurement [92] (68% confidence level):

$$\Omega_{\text{DM}} h^2 = 0.1198 \pm 0.0015. \quad (3.1)$$

In our model, the RHN DM particles mainly annihilate into the SM particles through the  $s$ -channel process mediated by the  $U(1)'$  gauge boson  $Z'$ .

The Boltzmann equation of the RHN DM is given by

$$\frac{dY}{dx} = -\frac{xs\langle\sigma v\rangle}{H(m_{\text{DM}})} (Y^2 - Y_{\text{EQ}}^2), \quad (3.2)$$

where temperature of the Universe is normalized by the mass of the RHN DM  $x = m_{\text{DM}}/T$ ,  $H(m_{\text{DM}})$  is the Hubble parameter at  $T = m_{\text{DM}}$ ,  $s$  is the entropy density,  $Y = n/s$  is the yield of the RHN DM which is defined by the ratio of the number density  $n$  to  $s$ ,  $Y_{\text{EQ}}$  is the yield in the

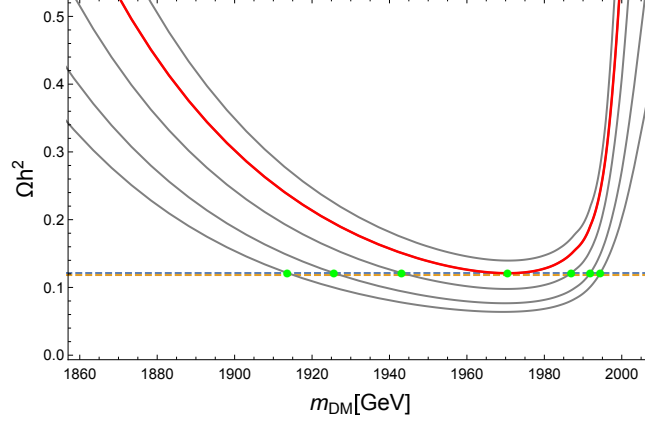


Figure 2: The relic density of the RHN DM as a function of its mass ( $m_{\text{DM}}$ ). We have fixed  $x_H = -0.575$  and  $m_{Z'} = 4$  TeV, and have shown the relic densities for various values of the gauge coupling,  $\alpha_{g_X} = 0.002, 0.00235, 0.003, 0.004$  and  $0.005$  (solid lines from top to bottom). The two horizontal lines denote the range of the observed DM relic density,  $0.1183 \leq \Omega_{\text{DM}} h^2 \leq 0.1213$  in the Planck 2015 results [92].

thermal equilibrium, and  $\langle \sigma v \rangle$  is the thermal averaged product of the RHN DM annihilation cross section  $\sigma$  and relative velocity  $v$ . Explicit formulas of these are summarized as follows:

$$\begin{aligned}
 s &= \frac{2\pi^2}{45} g_* \frac{m_{\text{DM}}^3}{x^3}, \\
 H(m_{\text{DM}}) &= \sqrt{\frac{\pi^2}{90} g_*} \frac{m_{\text{DM}}^2}{M_{\text{P}}}, \\
 sY_{\text{EQ}} &= \frac{g_{\text{DM}}}{2\pi^2} \frac{m_{\text{DM}}^3}{x} K_2(x),
 \end{aligned} \tag{3.3}$$

where  $g_{\text{DM}} = 2$  is the number of degrees of the freedom for the RHN DM,  $g_*$  is the effective total number of degrees of freedom for particles in thermal equilibrium (in this paper, we set  $g_* = 106.75$  for the SM particles), and  $K_2$  is the modified Bessel function of the second kind. The thermally-averaged annihilation cross section times velocity is given by

$$\langle \sigma v \rangle = (sY_{\text{EQ}})^{-2} g_{\text{DM}}^2 \frac{m_{\text{DM}}}{64\pi^4 x} \int_{4m_{\text{DM}}^2}^{\infty} ds \hat{\sigma}(s) \sqrt{s} K_1\left(\frac{x\sqrt{s}}{m_{\text{DM}}}\right), \tag{3.4}$$

where the reduced cross section is defined as  $\hat{\sigma}(s) = 2(s - 4m_{\text{DM}}^2)\sigma(s)$  with the total cross section  $\sigma(s)$ ,  $K_1$  is the modified Bessel function of the first kind. The total cross section of the

RHN DM annihilation process  $\nu_R^3 \nu_R^3 \rightarrow Z' \rightarrow f \bar{f}$  ( $f$  denotes the SM fermion) is calculated as

$$\begin{aligned} \sigma(s) &= \frac{\pi}{3} \alpha_{g_X}^2 \frac{\sqrt{s(s-4m_{\text{DM}}^2)}}{(s-m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \\ &\times \left[ \frac{103x_H^2 + 86x_H + 37}{3} + \frac{17x_H^2 + 10x_H + 2 + (7x_H^2 + 20x_H + 4)\frac{m_t^2}{s}}{3} \sqrt{1 - \frac{4m_t^2}{s}} \right. \\ &\quad \left. + 18x_H^2 \frac{(s-m_{Z'}^2)^2}{s(s-4m_{\text{DM}}^2)} \frac{m_{\text{DM}}^2 m_t^2}{m_{Z'}^4} \sqrt{1 - \frac{4m_t^2}{s}} \right], \end{aligned} \quad (3.5)$$

where the total decay width of  $Z'$  boson is given by

$$\begin{aligned} \Gamma_{Z'} &= \frac{\alpha_{g_X} m_{Z'}}{6} \left[ \frac{103x_H^2 + 86x_H + 37}{3} + \frac{17x_H^2 + 10x_H + 2 + (7x_H^2 + 20x_H + 4)\frac{m_t^2}{m_{Z'}^2}}{3} \sqrt{1 - \frac{4m_t^2}{m_{Z'}^2}} \right. \\ &\quad \left. + 2 \left( 1 - \frac{4m_N^2}{m_{Z'}^2} \right)^{\frac{3}{2}} \theta \left( \frac{m_{Z'}^2}{m_N^2} - 4 \right) + \left( 1 - \frac{4m_{\text{DM}}^2}{m_{Z'}^2} \right)^{\frac{3}{2}} \theta \left( \frac{m_{Z'}^2}{m_{\text{DM}}^2} - 4 \right) \right]. \end{aligned} \quad (3.6)$$

Here, we have neglected all SM fermion masses except for the top quark mass  $m_t$ .

By solving the Boltzmann Eq. (3.2) numerically, we find the asymptotic value of the yield  $Y(\infty)$ , and the present DM relic density is given by

$$\Omega_{\text{DM}} h^2 = \frac{m_{\text{DM}} s_0 Y(\infty)}{\rho_c / h^2}, \quad (3.7)$$

where  $s_0 = 2890 \text{ cm}^{-3}$  is the entropy density of the present Universe, and  $\rho_c / h^2 = 1.05 \times 10^{-5} \text{ GeV/cm}^3$  is the critical density. Our analysis involves four parameters, namely  $\alpha_{g_X}$ ,  $m_{Z'}$ ,  $m_{\text{DM}}$  and  $x_H$ . For  $m_{Z'} = 4 \text{ TeV}$  and  $x_H = -0.575$ , we show in Fig. 2 the resultant RHN DM relic density as a function of the RHN DM mass  $m_{\text{DM}}$ , along with the range of the observed DM relic density,  $0.1183 \leq \Omega_{\text{DM}} h^2 \leq 0.1213$  [92] (two horizontal dashed lines). The solid lines from top to bottom show the resultant RHN DM relic densities for various values of the gauge coupling,  $\alpha_{g_X} = 0.002, 0.00235, 0.003, 0.004$  and  $0.005$ . The plots indicate the lower bound on  $\alpha_{g_X} \geq 0.00235$  for  $m_{Z'} = 4 \text{ TeV}$  and  $x_H = -0.575$  in order to reproduce the observed relic density. In addition, we can see that the enhancement of the RHN DM annihilation cross section via the  $Z'$  boson resonance is necessary to satisfy the cosmological constraint and hence,  $m_{\text{DM}} \simeq m_{Z'}/2$ .

## 4 Collider constraints on the $U(1)'$ $Z'$ boson

The ATLAS and the CMS Collaborations have searched for  $Z'$  boson resonance at the LHC Run-1 with  $\sqrt{s} = 8 \text{ TeV}$ , and continued the search at the LHC Run-2 with  $\sqrt{s} = 13 \text{ TeV}$ . The most stringent bounds on the  $Z'$  boson production cross section times branching ratio have been obtained by using the dilepton final state. For the so-called sequential SM  $Z'$  ( $Z'_{\text{SSM}}$ ) model [103], where the  $Z'_{\text{SSM}}$  boson has exactly the same couplings with the SM fermions as

those of the SM  $Z$  boson, the latest cross section bounds from the LHC Run-2 results lead to lower bounds on the  $Z'_{SSM}$  boson mass as  $m_{Z'_{SSM}} \geq 4.05$  TeV in the ATLAS 2016 results [93] and  $m_{Z'_{SSM}} \geq 4.0$  TeV in the CMS 2016 results [94], respectively. We interpret these ATLAS and CMS results into the  $U(1)'$   $Z'$  boson case and derive constraints on  $x_H$ ,  $\alpha_{g_X}$  and  $m_{Z'}$ .

We calculate the dilepton production cross section for the process  $pp \rightarrow Z' + X \rightarrow \ell^+ \ell^- + X$ . The differential cross section with respect to the invariant mass  $M_{\ell\ell}$  of the final state dilepton is described as

$$\frac{d\sigma}{dM_{\ell\ell}} = \sum_{a,b} \int_{\frac{M_{\ell\ell}^2}{E_{\text{CM}}^2}}^1 dx_1 \frac{2M_{\ell\ell}}{x_1 E_{\text{CM}}^2} f_a(x_1, M_{\ell\ell}^2) f_b\left(\frac{M_{\ell\ell}^2}{x_1 E_{\text{CM}}^2}, M_{\ell\ell}^2\right) \hat{\sigma}(\bar{q}q \rightarrow Z' \rightarrow \ell^+ \ell^-), \quad (4.1)$$

where  $f_a$  is the parton distribution function for a parton  $a$ , and  $E_{\text{CM}} = 13$  TeV is the center-of-mass energy of the LHC Run-2. In our numerical analysis, we employ CTEQ5M [104] for the parton distribution functions. In the case of the  $U(1)'$  model, the cross sections for the colliding partons are given by

$$\begin{aligned} \hat{\sigma}(\bar{u}u \rightarrow Z' \rightarrow \ell^+ \ell^-) &= \frac{\pi \alpha_{g_X}^2}{81} \frac{M_{\ell\ell}^2}{(M_{\ell\ell}^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} (85x_H^4 + 152x_H^3 + 104x_H^2 + 32x_H + 4), \\ \hat{\sigma}(\bar{d}d \rightarrow Z' \rightarrow \ell^+ \ell^-) &= \frac{\pi \alpha_{g_X}^2}{81} \frac{M_{\ell\ell}^2}{(M_{\ell\ell}^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} (25x_H^4 + 20x_H^3 + 8x_H^2 + 8x_H + 4), \end{aligned} \quad (4.2)$$

where the total decay width of the  $Z'$  boson is given in Eq. (3.6). By integrating the differential cross section over a range of  $M_{\ell\ell}$  set by the ATLAS and CMS analyses, respectively, we obtain the cross section as a function of  $x_H$ ,  $\alpha_{g_X}$  and  $m_{Z'}$ , which are compared with the lower bounds obtained by the ATLAS and CMS Collaborations.

In interpreting the ATLAS and the CMS results for the  $U(1)'$   $Z'$  boson, we follow the strategy in [78]. We first analyze the sequential SM  $Z'$  model to check the consistency of our analysis with the one by the ATLAS and the CMS Collaborations. With the same couplings as the SM, we calculate the differential cross section of the process  $pp \rightarrow Z'_{SSM} + X \rightarrow \ell^+ \ell^- + X$  like Eq. (4.1). According to the analysis by the ATLAS Collaboration at the LHC Run-2, we integrate the differential cross section for the range of  $120 \text{ GeV} \leq M_{\ell\ell} \leq 6000 \text{ GeV}$  [93] and obtain the cross section of the dilepton production process as a function of the  $Z'_{SSM}$  boson mass. Our result is shown as a solid line in Fig. 3(a), along with the plots presented by the ATLAS Collaboration [93] (Here we have also shown the ALTAS 2015 result [54] for comparison. We can see that the ATLAS 2016 result has dramatically improved the bound obtained by the ATLAS 2015 result.). In Fig. 3(a), the experimental upper bounds on the  $Z'$  boson production cross section are depicted as the horizontal solid (red) curves. The theoretical  $Z'$  boson production cross section presented in [93] is shown as the diagonal dashed line, and the lower limit of the  $Z'_{SSM}$  boson mass is found to be 4.05 TeV, which can be read off from the intersection point of the theoretical prediction (diagonal dashed line) and the experimental cross section bound (horizontal lower solid (red) curve). In order to take into account the difference of the parton distribution functions used in the ATLAS analysis and our analysis, and QCD corrections of the process, we have scaled our resultant cross section by a factor  $k = 1.16$  in Fig. 3(a), with which we can obtain the same lower limit of the  $Z'_{SSM}$  boson mass as 4.05 TeV. We can see that our result (solid line) in Fig. 3(a) with the factor of  $k = 1.16$  is

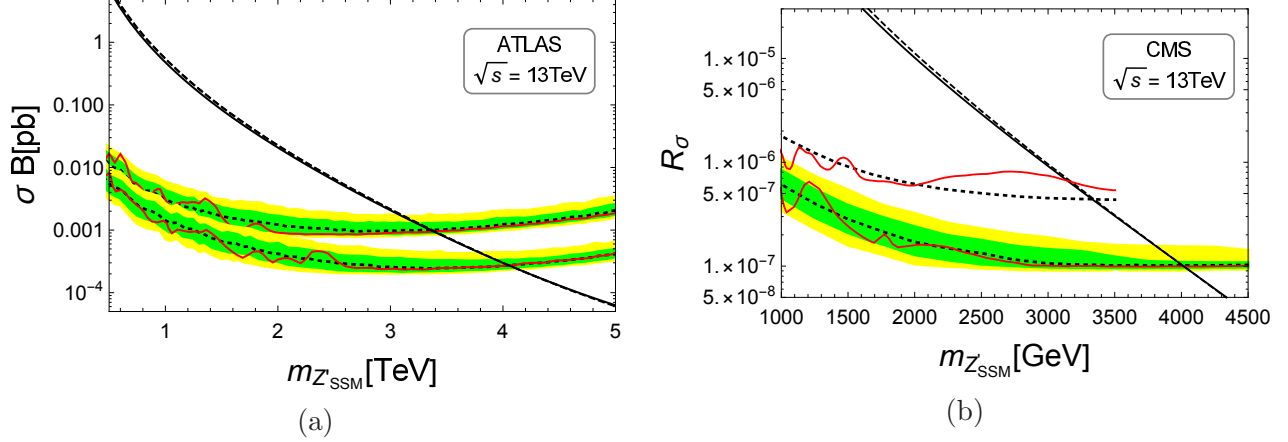


Figure 3: (a) The cross section as a function of the  $Z'_{SSM}$  mass (solid line) with  $k = 1.16$ , along with the LHC Run-2 ATLAS result from the combined dielectron and dimuon channels in Ref. [93]. (Here we have also shown the ATLAS 2015 result [54] for comparison.) (b) The cross section ratio as a function of the  $Z'_{SSM}$  mass (solid line) with  $k = 1.42$ , along with the LHC Run-2 CMS result from the combined dielectron and dimuon channels in Ref. [94]. (Here we have also shown the CMS 2015 result [55] for comparison.)

very consistent with the theoretical prediction (diagonal dashed line) presented by the ATLAS Collaboration. We use this factor in the following analysis for the  $U(1)' Z'$  production process, when we interpret the ATLAS 2016 result.

We apply the same strategy and compare our results for the  $Z'_{SSM}$  model with those in the CMS 2016 results [94]. According to the analysis by the CMS Collaboration, we integrate the differential cross section for the range of  $0.95 m_{Z'_{SSM}} \leq M_{\ell\ell} \leq 1.05 m_{Z'_{SSM}}$  [94] and obtain the cross section. In the CMS analysis, the limits are set on the ratio of the  $Z'_{SSM}$  boson cross section to the  $Z/\gamma^*$  cross section:

$$R_\sigma = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)}, \quad (4.3)$$

where the  $Z/\gamma^*$  production cross sections in the mass window of  $60 \text{ GeV} \leq M_{\ell\ell} \leq 120 \text{ GeV}$  are predicted to be 1928 pb at the LHC Run-2 [94]. Our result for the  $Z'_{SSM}$  model is shown as the solid line in Fig. 3(b), along with the plot presented in [94] (Here we have also shown the CMS 2015 result [55] for comparison. We can see that the CMS 2016 result has dramatically improved the bound obtained by the CMS 2015 result.). The analyses in this CMS paper leads to the lower limits of the  $Z'_{SSM}$  boson mass as 4.0 TeV, which is read off from the intersection point of the theoretical prediction (diagonal dashed line) and the experimental cross section bound (horizontal lower solid (red) curve). In order to obtain the same lower mass limits, we have scaled our resultant cross section by a factor  $k = 1.42$  in Fig. 3(b). With this  $k$  factor, our result (solid line) is very consistent with the theoretical prediction (diagonal dashed line) presented in Ref. [94]. We use this  $k$  factor in our analysis to interpret the CMS result for the  $U(1)' Z'$  boson case.

The search for effective 4-Fermi interactions mediated by the  $Z'$  boson at the LEP leads to a lower bound on  $m_{Z'}/g_X$  [95–97]. Employing the limits from the final LEP 2 data [97] at 95%

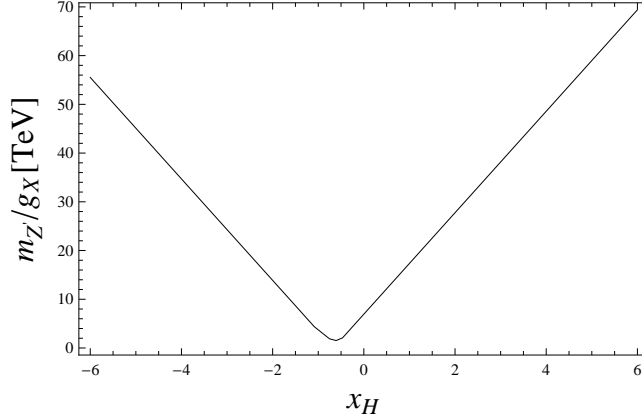


Figure 4: The lower bound on  $m_{Z'}/g_X$  as a function of  $x_H$ , obtained by the limits from the final LEP 2 data [97] at 95% confidence level.

confidence level, we follow Ref. [96] and derive a lower bound on  $m_{Z'}/g_X$  as a function  $x_H$ . Our result is shown in Fig. 4.

## 5 Combined results

Now let us combine all the constraints that we have obtained in the previous sections from the RHN DM physics, collider phenomenology, and the electroweak vacuum stability. In Fig. 5, we show the allowed region in the  $(m_{Z'}, \alpha_{g_X})$ -plain for fixed  $x_H = -0.575$ , as an example. The shaded region indicates the parameter space for solving the electroweak vacuum instability. The (blue) right solid line shows the lower bound on  $\alpha_{g_X}$  as a function of  $m_{Z'}$  to reproduce the observed DM relic density of the Planck result [92]. The (red) left solid (dashed) line shows the upper bound on  $\alpha_{g_X}$  obtained from the search results for  $Z'$  boson resonance by the CMS [94] (ATLAS [93]) Collaboration. The (green) shaded region in between two solid lines satisfies all constraints. These three constraints are complementary to narrow down the allowed region to be  $4 \text{ TeV} \lesssim m_{Z'} \lesssim 8 \text{ TeV}$  and  $0.009 \lesssim \alpha_{g_X} \lesssim 0.017$ . We also show the naturalness bounds for 10% (right dotted line) and 30% (left dotted line) fine-tuning levels.

In Fig. 6, we show allowed parameter regions in the  $(x_H, \alpha_{g_X})$ -plain for various  $m_{Z'}$  values. Fig. 6(a) is for  $m_{Z'} = 4 \text{ TeV}$ . The shaded region indicates the parameter space for solving the electroweak vacuum instability. The (blue) convex-downward solid line shows the lower bound on  $\alpha_{g_X}$  as a function of  $x_H$  to reproduce the observed DM relic density. The (red) convex-upward solid (dashed) line shows the upper bound on  $\alpha_{g_X}$  obtained from the search results for  $Z'$  boson resonance by the CMS [94] (ATLAS [93]) Collaboration, and the (red) dashed-dotted lines also show the LEP bounds. The (green) shaded region in between two solid lines satisfies all constraints. These three constraints are complementary to narrow down the allowed region to be  $-1.1 \lesssim x_H \lesssim -0.4$  and  $0.002 \lesssim \alpha_{g_X} \lesssim 0.02$ . We also show the naturalness bounds for 10% (dashed line) and 30% (dotted line) fine-tuning levels. Figs. 6(b), 6(c) and 6(d) are the same as Fig. 6(a), but  $m_{Z'} = 3.75 \text{ TeV}$ ,  $3.5 \text{ TeV}$  and  $3 \text{ TeV}$ , respectively.



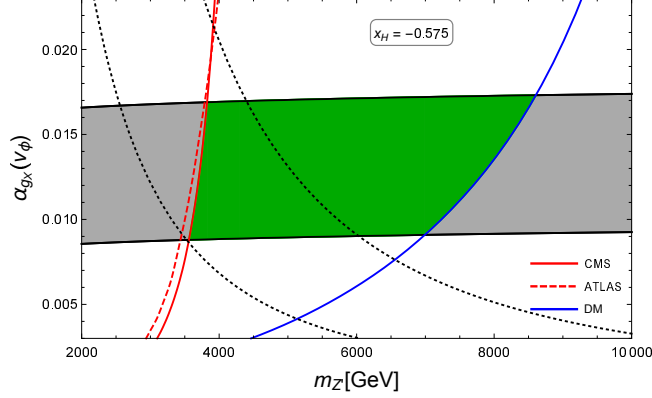


Figure 5: The allowed regions to solve the electroweak instability problem for  $m_{Z'}$  and  $\alpha_{g_X}$  with a fixed  $x_H = -0.575$  at the TeV scale, along with the dark matter lower bound ((blue) right solid line) on  $\alpha_{g_X}$ , the LHC Run-2 (2016) CMS upper bound ((red) solid line) on  $\alpha_{g_X}$  and the LHC Run-2 ATLAS (2016) upper bound ((red) dashed line) on  $\alpha_{g_X}$  from direct search for  $Z'$  boson resonance. The (green) shaded region in between two solid lines satisfies all constraints. Here, the naturalness bounds for 10% (right dotted line) and 30% (left dotted line) fine-tuning levels are also depicted.

From Fig. 6(b), the allowed region to satisfy these three constraints indicates  $-0.9 \lesssim x_H \lesssim -0.5$  and  $0.003 \lesssim \alpha_{g_X} \lesssim 0.015$  for fixed  $m_{Z'} = 3.75$  TeV. As  $m_{Z'}$  decreases, the LHC upper bound lines are shifted downward, while the DM lower bound line remains almost the same (it slightly moves to downward). Therefore, the allowed region between the LHC upper bounds and the DM lower bound narrows. On the other hand, the shaded region remains almost the same, so that the (green) shaded region disappears for  $m_{Z'} \lesssim 3.5$  TeV.

## 6 Conclusions

We have considered the DM scenario in the context of the classically conformal  $U(1)'$  extended SM, with three RHNs and the  $U(1)'$  Higgs field. The model is free from all the  $U(1)'$  gauge and gravitational anomalies in the presence of the three RHNs. We have introduced a  $Z_2$ -parity in the model, under which an odd-parity is assigned to one RHN, while all the other particles are assigned to be  $Z_2$ -even. In our model, the  $Z_2$ -odd RHN serves as a stable DM candidate, while the other two RHNs are utilized for the minimal seesaw mechanism in order to reproduce the neutrino oscillation data and the observed baryon asymmetry in the Universe through leptogenesis. In this model, the  $U(1)'$  gauge symmetry is radiatively broken through the CW mechanism, by which the electroweak symmetry breaking is triggered. There are three free parameters in our model, the  $U(1)'$  charge of the SM Higgs doublet ( $x_H$ ), the new  $U(1)'$  gauge coupling ( $\alpha_{g_X}$ ), and the  $U(1)'$  gauge boson ( $Z'$ ) mass ( $m_{Z'}$ ).

In this model context, we have first investigated a possibility to resolve the electroweak vacuum instability with the current world average of the experimental data,  $m_t = 173.34$  GeV and  $m_h = 125.09$  GeV. By analyzing the RG evolutions of the couplings of the model at the

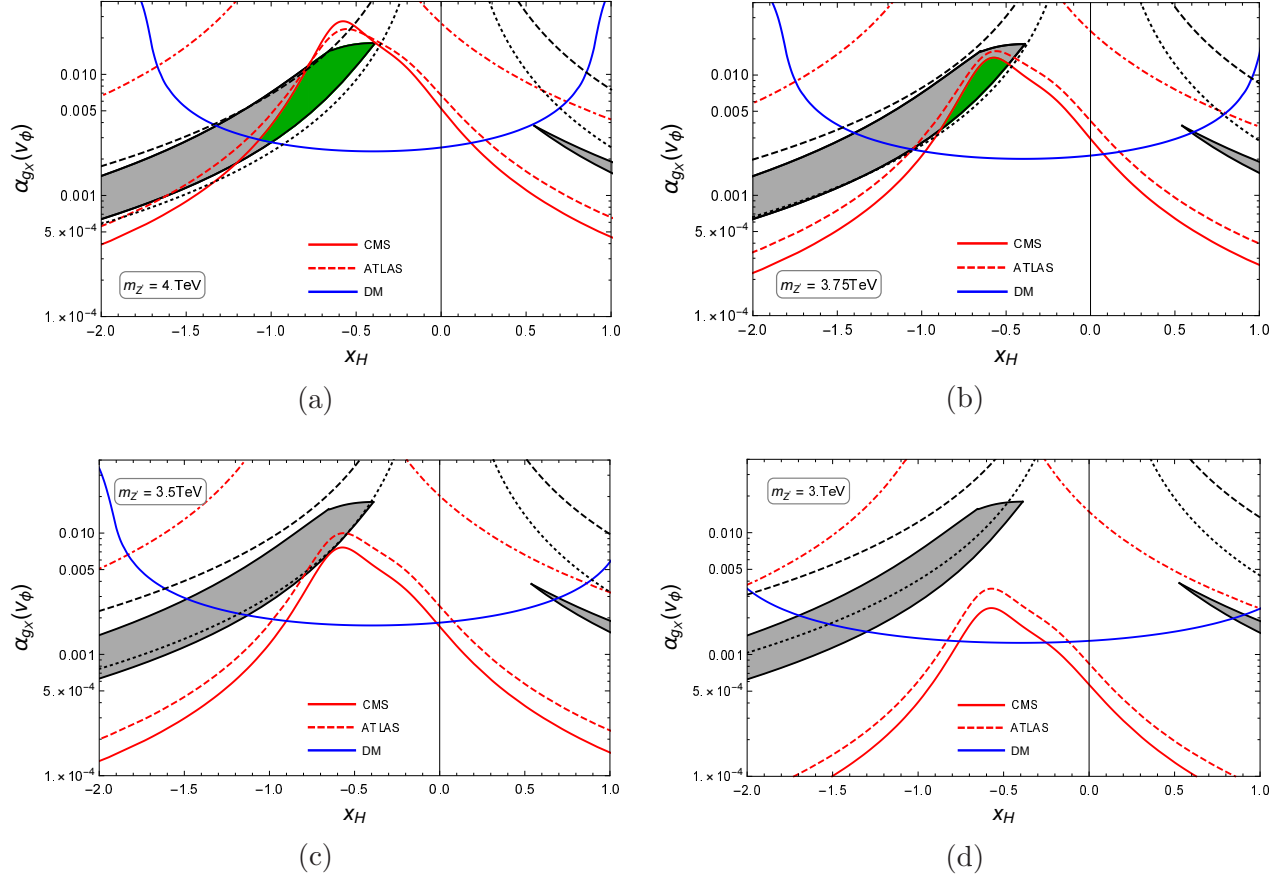


Figure 6: Allowed parameter regions in the  $(x_H, \alpha_{g_X})$ -plane for various  $m_{Z'}$  values. (a) is for  $m_{Z'} = 4$  TeV. The shaded region indicates the parameter space for solving the electroweak vacuum instability. The (blue) convex-downward solid line shows the cosmological lower bound on  $\alpha_{g_X}$  as a function of  $x_H$ . The (red) convex-upward solid (dashed) line shows the upper bound on  $\alpha_{g_X}$  obtained from the  $Z'$  boson search by the CMS [94] (ATLAS [93]) Collaboration, and the (red) dashed-dotted lines show the LEP bounds. The (green) shaded region in between two solid lines satisfies all constraints. Here, the naturalness bounds for 10% (dashed line) and 30% (dotted line) fine-tuning levels are also depicted. (b), (c) and (d) are the same as (a), but  $m_{Z'} = 3.75$  TeV, 3.5 TeV and 3 TeV, respectively.

two-loop level, we have performed a parameter scan for the three parameters,  $m_{Z'}$ ,  $\alpha_{g_X}$  and  $x_H$ , and have identified parameter regions which can solve the electroweak instability problem and keep all coupling values in the perturbative regime up to the Planck mass scale. We have found that the resultant parameter regions are very severely constrained. Next, we have calculated the thermal relic density of the RHN DM and identified the model parameter region to reproduce the observed DM relic density of the Planck 2015 measurement. In our model, the RHN DM particles mainly annihilate into the SM particles through the  $s$ -channel process mediated by the  $Z'$  boson. We have obtained the lower bound on  $\alpha_{g_X}$  as a function of  $m_{Z'}$  and  $x_H$  from the observed DM relic density. We have also considered the LHC Run-2 bounds from the search for the  $Z'$  boson resonance by the recent ATLAS and CMS analysis, which lead to the upper bounds on  $\alpha_{g_X}$  as a function of  $m_{Z'}$  and  $x_H$ . The LEP results from the search for effective 4-Fermi interactions mediated by the  $Z'$  boson can also constrain the model parameter space, but the LEP constraints are found to be weaker than those obtained from the LHC Run-2 results. Finally, we have combined all the constraints. The cosmological constraint on the RHN DM yields the lower bound on  $\alpha_{g_X}$  as a function of  $m_{Z'}$  and  $x_H$ , while the upper bound on  $\alpha_{g_X}$  is obtained from the LHC Run-2 results, so that these constraints are complementary to narrow the allowed parameter regions. We have found that only small portions in these allowed parameter regions can solve the electroweak vacuum instability problem. In particular, no allowed region to satisfy all constraints exists for  $m_{Z'} \lesssim 3.5$  TeV.

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## A APPENDIX

### References

- [1] P. Minkowski, “ $\mu \rightarrow e\gamma$  at a Rate of One Out of  $10^9$  Muon Decays?,” Phys. Lett. **B67** (1977) 421–428.
- [2] T. Yanagida, “HORIZONTAL SYMMETRY AND MASSES OF NEUTRINOS,” Conf. Proc. **C7902131** (1979) 95–99.
- [3] M. Gell-Mann, P. Ramond, and R. Slansky, “Complex Spinors and Unified Theories,” Conf. Proc. **C790927** (1979) 315–321, [arXiv:1306.4669 \[hep-th\]](#).
- [4] S. L. Glashow, “The Future of Elementary Particle Physics,” NATO Sci. Ser. B **61** (1980) 687.

- [5] R. N. Mohapatra and G. Senjanovic, “Neutrino Mass and Spontaneous Parity Violation,” *Phys. Rev. Lett.* **44** (1980) 912.
- [6] R. N. Mohapatra and R. E. Marshak, “Local B-L Symmetry of Electroweak Interactions, Majorana Neutrinos and Neutron Oscillations,” *Phys. Rev. Lett.* **44** (1980) 1316–1319. [Erratum: *Phys. Rev. Lett.* 44,1643(1980)].
- [7] R. E. Marshak and R. N. Mohapatra, “Quark - Lepton Symmetry and B-L as the U(1) Generator of the Electroweak Symmetry Group,” *Phys. Lett.* **B91** (1980) 222–224.
- [8] C. Wetterich, “Neutrino Masses and the Scale of B-L Violation,” *Nucl. Phys.* **B187** (1981) 343–375.
- [9] A. Masiero, J. F. Nieves, and T. Yanagida, “ $B - L$  Violating Proton Decay and Late Cosmological Baryon Production,” *Phys. Lett.* **B116** (1982) 11–15.
- [10] R. N. Mohapatra and G. Senjanovic, “Spontaneous Breaking of Global  $B - L$  Symmetry and Matter - Antimatter Oscillations in Grand Unified Theories,” *Phys. Rev.* **D27** (1983) 254.
- [11] W. Buchmuller, C. Greub, and P. Minkowski, “Neutrino masses, neutral vector bosons and the scale of B-L breaking,” *Phys. Lett.* **B267** (1991) 395–399.
- [12] T. Appelquist, B. A. Dobrescu, and A. R. Hopper, “Nonexotic neutral gauge bosons,” *Phys. Rev.* **D68** (2003) 035012, [arXiv:hep-ph/0212073](#) [[hep-ph](#)].
- [13] S. Oda, N. Okada, and D.-s. Takahashi, “Classically conformal U(1)’ extended standard model and Higgs vacuum stability,” *Phys. Rev.* **D92** no. 1, (2015) 015026, [arXiv:1504.06291](#) [[hep-ph](#)].
- [14] A. Das, S. Oda, N. Okada, and D.-s. Takahashi, “Classically conformal U(1)’ extended standard model, electroweak vacuum stability, and LHC Run-2 bounds,” *Phys. Rev.* **D93** no. 11, (2016) 115038, [arXiv:1605.01157](#) [[hep-ph](#)].
- [15] R. Hempfling, “The Next-to-minimal Coleman-Weinberg model,” *Phys. Lett.* **B379** (1996) 153–158, [arXiv:hep-ph/9604278](#) [[hep-ph](#)].
- [16] A. G. Dias, “Neutrino Mass Through Concomitant Breakdown of the U(1) Chiral and Scale Symmetries,” *Phys. Rev.* **D73** (2006) 096002, [arXiv:hep-ph/0604219](#) [[hep-ph](#)].
- [17] J. R. Espinosa and M. Quiros, “Novel Effects in Electroweak Breaking from a Hidden Sector,” *Phys. Rev.* **D76** (2007) 076004, [arXiv:hep-ph/0701145](#) [[hep-ph](#)].
- [18] W.-F. Chang, J. N. Ng, and J. M. S. Wu, “Shadow Higgs from a scale-invariant hidden U(1)(s) model,” *Phys. Rev.* **D75** (2007) 115016, [arXiv:hep-ph/0701254](#) [[HEP-PH](#)].
- [19] R. Foot, A. Kobakhidze, and R. R. Volkas, “Electroweak Higgs as a pseudo-Goldstone boson of broken scale invariance,” *Phys. Lett.* **B655** (2007) 156–161, [arXiv:0704.1165](#) [[hep-ph](#)].

- [20] R. Foot, A. Kobakhidze, K. McDonald, and R. Volkas, “Neutrino mass in radiatively-broken scale-invariant models,” *Phys. Rev.* **D76** (2007) 075014, [arXiv:0706.1829 \[hep-ph\]](#).
- [21] K. A. Meissner and H. Nicolai, “Conformal Symmetry and the Standard Model,” *Phys. Lett.* **B648** (2007) 312–317, [arXiv:hep-th/0612165 \[hep-th\]](#).
- [22] R. Foot, A. Kobakhidze, K. L. McDonald, and R. R. Volkas, “A Solution to the hierarchy problem from an almost decoupled hidden sector within a classically scale invariant theory,” *Phys. Rev.* **D77** (2008) 035006, [arXiv:0709.2750 \[hep-ph\]](#).
- [23] K. A. Meissner and H. Nicolai, “Effective action, conformal anomaly and the issue of quadratic divergences,” *Phys. Lett.* **B660** (2008) 260–266, [arXiv:0710.2840 \[hep-th\]](#).
- [24] K. A. Meissner and H. Nicolai, “Neutrinos, Axions and Conformal Symmetry,” *Eur. Phys. J.* **C57** (2008) 493–498, [arXiv:0803.2814 \[hep-th\]](#).
- [25] S. Iso, N. Okada, and Y. Orikasa, “Classically conformal  $B - L$  extended Standard Model,” *Phys. Lett.* **B676** (2009) 81–87, [arXiv:0902.4050 \[hep-ph\]](#).
- [26] S. Iso, N. Okada, and Y. Orikasa, “The minimal B-L model naturally realized at TeV scale,” *Phys. Rev.* **D80** (2009) 115007, [arXiv:0909.0128 \[hep-ph\]](#).
- [27] M. Holthausen, M. Lindner, and M. A. Schmidt, “Radiative Symmetry Breaking of the Minimal Left-Right Symmetric Model,” *Phys. Rev.* **D82** (2010) 055002, [arXiv:0911.0710 \[hep-ph\]](#).
- [28] A. Farzinnia, H.-J. He, and J. Ren, “Natural Electroweak Symmetry Breaking from Scale Invariant Higgs Mechanism,” *Phys. Lett.* **B727** (2013) 141–150, [arXiv:1308.0295 \[hep-ph\]](#).
- [29] M. Heikinheimo, A. Racioppi, M. Raidal, C. Spethmann, and K. Tuominen, “Physical Naturalness and Dynamical Breaking of Classical Scale Invariance,” *Mod. Phys. Lett.* **A29** (2014) 1450077, [arXiv:1304.7006 \[hep-ph\]](#).
- [30] A. Farzinnia and J. Ren, “Higgs Partner Searches and Dark Matter Phenomenology in a Classically Scale Invariant Higgs Boson Sector,” *Phys. Rev.* **D90** no. 1, (2014) 015019, [arXiv:1405.0498 \[hep-ph\]](#).
- [31] M. Lindner, S. Schmidt, and J. Smirnov, “Neutrino Masses and Conformal Electro-Weak Symmetry Breaking,” *JHEP* **10** (2014) 177, [arXiv:1405.6204 \[hep-ph\]](#).
- [32] V. V. Khoze, C. McCabe, and G. Ro, “Higgs vacuum stability from the dark matter portal,” *JHEP* **08** (2014) 026, [arXiv:1403.4953 \[hep-ph\]](#).
- [33] E. Gabrielli, M. Heikinheimo, K. Kannike, A. Racioppi, M. Raidal, and C. Spethmann, “Towards Completing the Standard Model: Vacuum Stability, EWSB and Dark Matter,” *Phys. Rev.* **D89** no. 1, (2014) 015017, [arXiv:1309.6632 \[hep-ph\]](#).

- [34] W. Altmannshofer, W. A. Bardeen, M. Bauer, M. Carena, and J. D. Lykken, “Light Dark Matter, Naturalness, and the Radiative Origin of the Electroweak Scale,” JHEP **01** (2015) 032, [arXiv:1408.3429 \[hep-ph\]](#).
- [35] A. Karam and K. Tamvakis, “Dark matter and neutrino masses from a scale-invariant multi-Higgs portal,” Phys. Rev. **D92** no. 7, (2015) 075010, [arXiv:1508.03031 \[hep-ph\]](#).
- [36] N. Haba, H. Ishida, N. Okada, and Y. Yamaguchi, “Electroweak symmetry breaking through bosonic seesaw mechanism in a classically conformal extension of the Standard Model,” [arXiv:1509.01923 \[hep-ph\]](#).
- [37] H. Okada, Y. Orikasa, and K. Yagyu, “Higgs Triplet Model with Classically Conformal Invariance,” [arXiv:1510.00799 \[hep-ph\]](#).
- [38] A. Latosinski, A. Lewandowski, K. A. Meissner, and H. Nicolai, “Conformal Standard Model with an extended scalar sector,” JHEP **10** (2015) 170, [arXiv:1507.01755 \[hep-ph\]](#).
- [39] Z.-W. Wang, F. S. Sage, T. G. Steele, and R. B. Mann, “Asymptotic Safety in the Conformal Hidden Sector?,” [arXiv:1511.02531 \[hep-ph\]](#).
- [40] F. Goertz, “Electroweak Symmetry Breaking without the  $\mu^2$  Term,” Phys. Rev. **D94** no. 1, (2016) 015013, [arXiv:1504.00355 \[hep-ph\]](#).
- [41] N. Haba, H. Ishida, N. Okada, and Y. Yamaguchi, “Bosonic seesaw mechanism in a classically conformal extension of the Standard Model,” Phys. Lett. **B754** (2016) 349–352, [arXiv:1508.06828 \[hep-ph\]](#).
- [42] N. Haba, H. Ishida, R. Takahashi, and Y. Yamaguchi, “Gauge coupling unification in a classically scale invariant model,” JHEP **02** (2016) 058, [arXiv:1511.02107 \[hep-ph\]](#).
- [43] K. Ghorbani and H. Ghorbani, “Scalar Dark Matter in Scale Invariant Standard Model,” JHEP **04** (2016) 024, [arXiv:1511.08432 \[hep-ph\]](#).
- [44] N. Haba, H. Ishida, N. Kitazawa, and Y. Yamaguchi, “A new dynamics of electroweak symmetry breaking with classically scale invariance,” Phys. Lett. **B755** (2016) 439–443, [arXiv:1512.05061 \[hep-ph\]](#).
- [45] A. Ahriche, K. L. McDonald, and S. Nasri, “A Radiative Model for the Weak Scale and Neutrino Mass via Dark Matter,” JHEP **02** (2016) 038, [arXiv:1508.02607 \[hep-ph\]](#).
- [46] H. Ishida, S. Matsuzaki, and Y. Yamaguchi, “Invisible axionlike dark matter from the electroweak bosonic seesaw mechanism,” Phys. Rev. **D94** no. 9, (2016) 095011, [arXiv:1604.07712 \[hep-ph\]](#).
- [47] H. Hatanaka, D.-W. Jung, and P. Ko, “AdS/QCD approach to the scale-invariant extension of the standard model with a strongly interacting hidden sector,” JHEP **08** (2016) 094, [arXiv:1606.02969 \[hep-ph\]](#).



- [48] A. Karam and K. Tamvakis, “Dark Matter from a Classically Scale-Invariant  $SU(3)_X$ ,” *Phys. Rev.* **D94** no. 5, (2016) 055004, [arXiv:1607.01001 \[hep-ph\]](#).
- [49] A. Das, N. Okada, and N. Papapietro, “Electroweak vacuum stability in classically conformal B-L extension of the Standard Model,” *Eur. Phys. J.* **C77** no. 2, (2017) 122, [arXiv:1509.01466 \[hep-ph\]](#).
- [50] K. Kannike, M. Raidal, C. Spethmann, and H. Veerme, “Evolving Planck Mass in Classically Scale-Invariant Theories,” *JHEP* **04** (2017) 026, [arXiv:1610.06571 \[hep-ph\]](#).
- [51] S. R. Coleman and E. J. Weinberg, “Radiative Corrections as the Origin of Spontaneous Symmetry Breaking,” *Phys. Rev.* **D7** (1973) 1888–1910.
- [52] **ATLAS, CDF, CMS, D0** Collaboration, “First combination of Tevatron and LHC measurements of the top-quark mass,” [arXiv:1403.4427 \[hep-ex\]](#).
- [53] **ATLAS, CMS** Collaboration, G. Aad *et al.*, “Combined Measurement of the Higgs Boson Mass in  $pp$  Collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS and CMS Experiments,” *Phys. Rev. Lett.* **114** (2015) 191803, [arXiv:1503.07589 \[hep-ex\]](#).
- [54] T. A. collaboration, “Search for new phenomena in the dilepton final state using proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” ATLAS-CONF-2015-070.
- [55] **CMS** Collaboration, C. Collaboration, “Search for a Narrow Resonance Produced in 13 TeV  $pp$  Collisions Decaying to Electron Pair or Muon Pair Final States,” CMS-PAS-EXO-15-005.
- [56] N. Okada and O. Seto, “Higgs portal dark matter in the minimal gauged  $U(1)_{B-L}$  model,” *Phys. Rev.* **D82** (2010) 023507, [arXiv:1002.2525 \[hep-ph\]](#).
- [57] A. Anisimov and P. Di Bari, “Cold Dark Matter from heavy Right-Handed neutrino mixing,” *Phys. Rev.* **D80** (2009) 073017, [arXiv:0812.5085 \[hep-ph\]](#).
- [58] M. Fukugita and T. Yanagida, “Baryogenesis Without Grand Unification,” *Phys. Lett.* **B174** (1986) 45–47.
- [59] S. F. King, “Large mixing angle MSW and atmospheric neutrinos from single right-handed neutrino dominance and  $U(1)$  family symmetry,” *Nucl. Phys.* **B576** (2000) 85–105, [arXiv:hep-ph/9912492 \[hep-ph\]](#).
- [60] P. H. Frampton, S. L. Glashow, and T. Yanagida, “Cosmological sign of neutrino CP violation,” *Phys. Lett.* **B548** (2002) 119–121, [arXiv:hep-ph/0208157 \[hep-ph\]](#).
- [61] Z. M. Burell and N. Okada, “Supersymmetric minimal B-L model at the TeV scale with right-handed Majorana neutrino dark matter,” *Phys. Rev.* **D85** (2012) 055011, [arXiv:1111.1789 \[hep-ph\]](#).

- [62] L. Basso, O. Fischer, and J. J. van der Bij, “Natural  $Z'$  model with an inverse seesaw mechanism and leptonic dark matter,” *Phys. Rev.* **D87** no. 3, (2013) 035015, [arXiv:1207.3250 \[hep-ph\]](#).
- [63] E. Dudas, L. Heurtier, Y. Mambrini, and B. Zaldivar, “Extra  $U(1)$ , effective operators, anomalies and dark matter,” *JHEP* **11** (2013) 083, [arXiv:1307.0005 \[hep-ph\]](#).
- [64] M. Das and S. Mohanty, “Leptophilic dark matter in gauged  $L_\mu - L_\tau$  extension of MSSM,” *Phys. Rev.* **D89** no. 2, (2014) 025004, [arXiv:1306.4505 \[hep-ph\]](#).
- [65] X. Chu, Y. Mambrini, J. Quevillon, and B. Zaldivar, “Thermal and non-thermal production of dark matter via  $Z'$ -portal(s),” *JCAP* **1401** (2014) 034, [arXiv:1306.4677 \[hep-ph\]](#).
- [66] M. Lindner, D. Schmidt, and A. Watanabe, “Dark matter and  $U(1)'$  symmetry for the right-handed neutrinos,” *Phys. Rev.* **D89** no. 1, (2014) 013007, [arXiv:1310.6582 \[hep-ph\]](#).
- [67] A. Alves, S. Profumo, and F. S. Queiroz, “The dark  $Z'$  portal: direct, indirect and collider searches,” *JHEP* **04** (2014) 063, [arXiv:1312.5281 \[hep-ph\]](#).
- [68] J. Kopp, L. Michaels, and J. Smirnov, “Loopy Constraints on Leptophilic Dark Matter and Internal Bremsstrahlung,” *JCAP* **1404** (2014) 022, [arXiv:1401.6457 \[hep-ph\]](#).
- [69] P. Agrawal, Z. Chacko, and C. B. Verhaaren, “Leptophilic Dark Matter and the Anomalous Magnetic Moment of the Muon,” *JHEP* **08** (2014) 147, [arXiv:1402.7369 \[hep-ph\]](#).
- [70] D. Hooper, “ $Z'$  Mediated Dark Matter Models for the Galactic Center Gamma-Ray Excess,” *Phys. Rev.* **D91** (2015) 035025, [arXiv:1411.4079 \[hep-ph\]](#).
- [71] E. Ma and R. Srivastava, “Dirac or inverse seesaw neutrino masses with  $B - L$  gauge symmetry and  $S_3$  flavor symmetry,” *Phys. Lett.* **B741** (2015) 217–222, [arXiv:1411.5042 \[hep-ph\]](#).
- [72] A. Alves, A. Berlin, S. Profumo, and F. S. Queiroz, “Dark Matter Complementarity and the  $Z'$  Portal,” *Phys. Rev.* **D92** no. 8, (2015) 083004, [arXiv:1501.03490 \[hep-ph\]](#).
- [73] K. Ghorbani and H. Ghorbani, “Two-portal Dark Matter,” *Phys. Rev.* **D91** no. 12, (2015) 123541, [arXiv:1504.03610 \[hep-ph\]](#).
- [74] B. L. Snchez-Vega and E. R. Schmitz, “Fermionic dark matter and neutrino masses in a B-L model,” *Phys. Rev.* **D92** (2015) 053007, [arXiv:1505.03595 \[hep-ph\]](#).
- [75] M. Duerr, P. Fileviez Perez, and J. Smirnov, “Simplified Dirac Dark Matter Models and Gamma-Ray Lines,” *Phys. Rev.* **D92** no. 8, (2015) 083521, [arXiv:1506.05107 \[hep-ph\]](#).

- [76] A. Alves, A. Berlin, S. Profumo, and F. S. Queiroz, “Dirac-fermionic dark matter in  $U(1)_X$  models,” JHEP **10** (2015) 076, [arXiv:1506.06767 \[hep-ph\]](#).
- [77] E. Ma, N. Pollard, R. Srivastava, and M. Zakeri, “Gauge  $B - L$  Model with Residual  $Z_3$  Symmetry,” Phys. Lett. **B750** (2015) 135–138, [arXiv:1507.03943 \[hep-ph\]](#).
- [78] N. Okada and S. Okada, “ $Z'_{BL}$  portal dark matter and LHC Run-2 results,” Phys. Rev. **D93** no. 7, (2016) 075003, [arXiv:1601.07526 \[hep-ph\]](#).
- [79] N. Okada and N. Papapietro, “R-parity Conserving Minimal SUSY  $B - L$  Model,” [arXiv:1603.01769 \[hep-ph\]](#).
- [80] W. Chao, H.-k. Guo, and Y. Zhang, “Majorana Dark matter with B+L gauge symmetry,” [arXiv:1604.01771 \[hep-ph\]](#).
- [81] A. Biswas, S. Choubey, and S. Khan, “Galactic gamma ray excess and dark matter phenomenology in a  $U(1)_{B-L}$  model,” JHEP **08** (2016) 114, [arXiv:1604.06566 \[hep-ph\]](#).
- [82] E. Accomando, C. Coriano, L. Delle Rose, J. Fiaschi, C. Marzo, and S. Moretti, “ $Z'$ , Higgses and heavy neutrinos in  $U(1)'$  models: from the LHC to the GUT scale,” JHEP **07** (2016) 086, [arXiv:1605.02910 \[hep-ph\]](#).
- [83] M. Fairbairn, J. Heal, F. Kahlhoefer, and P. Tunney, “Constraints on  $Z'$  models from LHC dijet searches and implications for dark matter,” JHEP **09** (2016) 018, [arXiv:1605.07940 \[hep-ph\]](#).
- [84] M. Klasen, F. Lyonnet, and F. S. Queiroz, “NLO+NLL Collider Bounds, Dirac Fermion and Scalar Dark Matter in the B-L Model,” [arXiv:1607.06468 \[hep-ph\]](#).
- [85] P. S. Bhupal Dev, R. N. Mohapatra, and Y. Zhang, “Naturally stable right-handed neutrino dark matter,” JHEP **11** (2016) 077, [arXiv:1608.06266 \[hep-ph\]](#).
- [86] W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, “Explaining dark matter and  $B$  decay anomalies with an  $L_\mu - L_\tau$  model,” JHEP **12** (2016) 106, [arXiv:1609.04026 \[hep-ph\]](#).
- [87] N. Okada and S. Okada, “ $Z'$ -portal right-handed neutrino dark matter in the minimal  $U(1)_X$  extended Standard Model,” Phys. Rev. **D95** no. 3, (2017) 035025, [arXiv:1611.02672 \[hep-ph\]](#).
- [88] K. Kaneta, Z. Kang, and H.-S. Lee, “Right-handed neutrino dark matter under the  $B - L$  gauge interaction,” JHEP **02** (2017) 031, [arXiv:1606.09317 \[hep-ph\]](#).
- [89] G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, S. Profumo, and F. S. Queiroz, “The Waning of the WIMP? A Review of Models, Searches, and Constraints,” [arXiv:1703.07364 \[hep-ph\]](#).

- [90] N. Okada and Y. Orikasa, “Dark matter in the classically conformal B-L model,” *Phys. Rev.* **D85** (2012) 115006, [arXiv:1202.1405 \[hep-ph\]](#).
- [91] T. Basak and T. Mondal, “Constraining Minimal  $U(1)_{B-L}$  model from Dark Matter Observations,” *Phys. Rev.* **D89** (2014) 063527, [arXiv:1308.0023 \[hep-ph\]](#).
- [92] **Planck** Collaboration, N. Aghanim *et al.*, “Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters,” *Astron. Astrophys.* **594** (2016) A11, [arXiv:1507.02704 \[astro-ph.CO\]](#).
- [93] **ATLAS** Collaboration, T. A. collaboration, “Search for new high-mass resonances in the dilepton final state using proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” ATLAS-CONF-2016-045.
- [94] **CMS** Collaboration, C. Collaboration, “Search for a high-mass resonance decaying into a dilepton final state in  $13 \text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 13$  TeV,” CMS-PAS-EXO-16-031.
- [95] **SLD Electroweak Group, SLD Heavy Flavor Group, DELPHI, LEP, ALEPH, OPAL, LEP Electroweak Working Group, L3** Collaboration, t. S. Electroweak, “A Combination of preliminary electroweak measurements and constraints on the standard model,” [arXiv:hep-ex/0312023 \[hep-ex\]](#).
- [96] M. Carena, A. Daleo, B. A. Dobrescu, and T. M. P. Tait, “ $Z'$  gauge bosons at the Tevatron,” *Phys. Rev.* **D70** (2004) 093009, [arXiv:hep-ph/0408098 \[hep-ph\]](#).
- [97] **DELPHI, OPAL, LEP Electroweak, ALEPH, L3** Collaboration, S. Schael *et al.*, “Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP,” *Phys. Rept.* **532** (2013) 119–244, [arXiv:1302.3415 \[hep-ex\]](#).
- [98] D. Buttazzo, G. Degrandi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio, and A. Strumia, “Investigating the near-criticality of the Higgs boson,” *JHEP* **12** (2013) 089, [arXiv:1307.3536 \[hep-ph\]](#).
- [99] C. Coriano, L. Delle Rose, and C. Marzo, “Vacuum Stability in  $U(1)$ -Prime Extensions of the Standard Model with TeV Scale Right Handed Neutrinos,” *Phys. Lett.* **B738** (2014) 13–19, [arXiv:1407.8539 \[hep-ph\]](#).
- [100] S. Di Chiara, V. Keus, and O. Lebedev, “Stabilizing the Higgs potential with a  $Z'$ ,” *Phys. Lett.* **B744** (2015) 59–66, [arXiv:1412.7036 \[hep-ph\]](#).
- [101] C. Coriano, L. Delle Rose, and C. Marzo, “Constraints on abelian extensions of the Standard Model from two-loop vacuum stability and  $U(1)_{B-L}$ ,” *JHEP* **02** (2016) 135, [arXiv:1510.02379 \[hep-ph\]](#).
- [102] J. A. Casas, J. R. Espinosa, and I. Hidalgo, “Implications for new physics from fine-tuning arguments. 1. Application to SUSY and seesaw cases,” *JHEP* **11** (2004) 057, [arXiv:hep-ph/0410298 \[hep-ph\]](#).

- [103] V. D. Barger, W.-Y. Keung, and E. Ma, “Doubling of Weak Gauge Bosons in an Extension of the Standard Model,” *Phys. Rev. Lett.* **44** (1980) 1169.
- [104] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky, and W. K. Tung, “New generation of parton distributions with uncertainties from global QCD analysis,” *JHEP* **07** (2002) 012, [arXiv:hep-ph/0201195](#) [[hep-ph](#)].